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Managing High Penetration of Renewable Energy in MV Grid By Electric Vehicle Storage

Reza Ahmadi Kordkheili, Birgitte Bak-Jensen, Jayakrishnan R. Pillai, Mehdi Savaghebi, and Josep M. Guerrero

Dept. Energy Technology
Aalborg University
Aalborg, Denmark
rak@et.aau.dk

Abstract— This paper proposes an intelligent algorithm for dealing with high penetration of renewable energy sources (RESs) in the medium voltage (MV) by intelligently managing electric vehicles (EVs), as one of the grid flexible loads. The MV grid used in this work is a CIGRE benchmark grid. Different residential and industrial loads are considered in this grid. The connection of medium voltage wind turbines to the grid is investigated. The solar panels in this study are residential panels. Also, EVs are located among the buses with residential demand. The study is done for different winter and summer scenarios, considering typical load profiles in Denmark. Different scenarios have been studied with different penetration level of RESs in the grid. The results show the capability of the proposed algorithm to reduce voltage deviations among the grid buses, as well as to increase the RES penetration in the grid by intelligent management of EVs.

Keywords— *electric vehicles; energy management; energy storage; modeling; renewable energy sources (RESs); solar energy; solar power generation; wind energy integration*

I. INTRODUCTION

Integrating large-scale renewable energy production, especially wind and solar energy, into the power system is a major challenge due to their variations and prediction errors [1]–[3]. Nowadays, wind energy is considered as one of the replacements for conventional power plants, as it has no fuel costs and has no pollution. In countries where this energy could not yet find its place in electrical industry, there is a trial to develop it using the incentive policies such as Renewable Portfolio Standard (RPS) [4]. Renewable policies such as fixed tariff in countries such as Germany, Denmark and Spain have made rapid progress of this energy [4]. Denmark is a leading country in Europe in the integration of wind energy in power system, with more than 39% of its electric consumption supplied by wind energy [5], [6]. Also, different policies and tariffs for supporting solar panels have been defined in the last few years, which have led to a significant increase in the penetration level of solar panels in the power system, especially in the residential areas [3]. However, as mentioned, high penetration of renewable energy in the system can be challenging, considering the uncertainty of these resources. Such uncertainties might lead to issues for the grid such as grid congestion, overvoltage or issues regarding line nominal currents [7]. On the other hand, new developments towards

smart grid concepts and technologies are expected to affect customers' behavior, and turn them into active participants in the power system and energy market [8]. Considering the role of information and communication technology in the smart grid and their ability to intelligently integrate the actions of the customers, flexible demand can be a major player in balancing the demand and supply, and maximizing the utilization of RESs in the system. Electric vehicles, as a promising technology, can play a significant role as the grid flexible demand. Despite the uncertain speed in the development of EVs, the number of EVs can grow fast and the impact of these flexible loads on the power system can be remarkable [8]. Fast evolution towards the smart grid in recent years has made it feasible to design and deploy different smart charging algorithms for EVs. Such potential leads to new opportunities for different parties to use the capacity and flexibility of EVs for different purposes and different objectives [9], [10]. Several strategies are designed to minimize the charging costs with respect to real-time price [9]. Also, in some strategies EVs are used for frequency regulation and/or real-time balancing of power [10]. Utilizing EVs for flattening peak demand is another interesting smart charging objective, because shifting the demand to off-peak hours increases the grid ability to transport the energy from the RESs to the upper grid, without reinforcing the grid structure [5].

This paper evaluates the impact of high RES penetration in an MV grid, without reinforcing the grid. The potential of EVs in dealing with high penetration of RESs in the system is also analyzed. A case study is carried out on a CIGRE standard MV grid benchmark [11]. Different scenarios are defined and analyzed based on load and generation profiles in summer and winter to find out the grid operating conditions. The rest of the paper is organized as follows. Section II explains the grid layout, the load type and demand. Also, the details of EVs are presented in section II. Section III explains the modeling and details of wind turbines and residential solar panels. The proposed algorithms for integration of RESs in the grid are developed in two cases in section IV, in which one case considers the effect of EVs in the grid, and the other one does not. Also, different winter and summer scenarios are proposed in section IV for a comprehensive study of the proposed algorithms. Simulation results and analysis under different scenarios are presented and discussed in section V. Section VI presents the conclusion of the work.

II. GRID LAYOUT AND LOAD MODELING

In this study, CIGRE MV grid benchmark is used as a case study, which is shown in Fig. 1 [11]. The grid consists of two 25 MVA medium voltage transformers. By default, all the circuit breakers are open in the grid. The grid is combined of residential and industrial loads, with different power factors and different demands. Table I presents the type and demand of loads on different grid buses [11]. Considering the available data for the system, the load modeling is explained in the following subsection.

A. Load Modeling

Modeling the load profiles of different industrial and residential loads are based on a measured Danish grid profile. To apply the study to the CIGRE network in Fig. 1, it is necessary to scale the bus demands in Table I with respect to Danish load profiles. In order to create load profiles, the demand profiles of each grid bus were created by scaling up the demand profiles with respect to typical load demand in Fig. 2. The scaling factors are with respect to the demands and power factors in Table I. Then, the load profile of each grid bus was adapted with respect to Danish profile. Considering the load modeling method and obtaining the energy consumption of different days in the year, the annual energy consumption of the grid is calculated to be 106385 MWh. Considering the annual energy demand of the grid, it is possible to increase the percentage of the grid demand which can be covered by RESs, without violating grid operating limits.

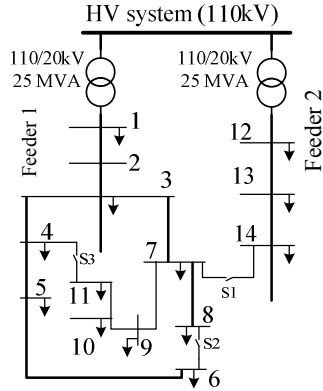


Fig. 1. Grid layout [11].

TABLE I. DEMAND ON EACH GRID BUS [11]

Node	Apparent Power (kVA)		Power Factor	
	Residential	Industrial	Residential	Industrial
1	15300	5100	.98	.98
2	----	----	----	----
3	285	265	.97	.85
4	445	----	.97	----
5	750	----	.97	----
6	565	----	.97	----
7	----	90	----	.85
8	605	----	.97	----
9	----	675	----	.97
10	490	80	.97	.85
11	340	----	.97	----
12	15300	5280	.98	.95
13	----	40	----	.85
14	9215	390	.97	.85

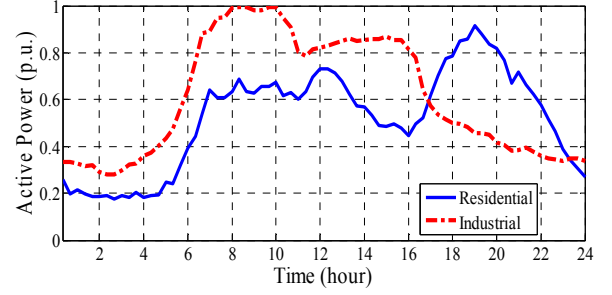


Fig. 2. Typical demand profile for residential and industrial load (p.u.).

TABLE II. DETAILS OF EVs IN THE GRID [14]

	% of EVs	Battery (kWh)	Average consumption (Wh/km)	Charger power (kW) (3-φ)	Average daily distance (km)
Commuter	80	30	150	7.2	40
Family car	20	30	150	7.2	25

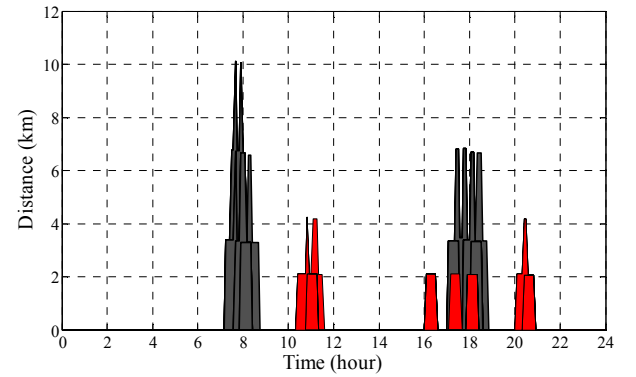


Fig. 3. DP of commuters (black) and family cars (red).

B. Electric Vehicle

The EV model used in this study is presented in [12], [13]. Two types of EVs are considered in this grid: commuters and family cars. Fig. 3 presents the distance profile (DP) of EVs in this study. It is assumed that when the EV is idle, it is connected to the grid. The EV specifications and the percentage of commuters and family cars for this study are presented in Table II [14]. Regardless of the number of EVs in different buses, the ratio of “commuter/family car” is similar. It should also be noted that EVs are located only at residential buses in Fig. 1, considering the type of the loads of each bus from Table I. As a worst case scenario, the EVs on each bus are the aggregated model of the EVs in that bus, i.e. it is assumed that the DPs of all the commuters, as well as the DPs of the family cars on each bus are similar.

III. RES IN THE GRID

A. Solar PV Panels

The solar PV panel modeling is done using (1) [3], [7].

$$P_{pv} = \frac{G}{G_{STC}} * P_{STC} (1 + \alpha(t - t_0)) \quad (1)$$

G is the irradiation, G_{STC} is the standard irradiance, α is the power temperature ($-0.00025/^\circ\text{C}$), t is the ambient temperature,

and t_0 is the standard temperature (25°C) [7]. As the main focus is on residential solar panels, only the grid buses with residential demand are considered for placement of PV panels. In all the studies, the penetration level of solar panels on different grid buses is similar, i.e. the number of panels on different buses is determined with respect to the residential demand of the bus.

$$E_{avg} = (E_{2012} + E_{2013} + E_{2014}) / 3 = 8917 \text{ MWh} \quad (2)$$

$$\% \text{ of annual consumption} = 8917 / 106385 = 8.38\%$$

IV. PROPOSED ALGORITHM

A. Without EVs

The proposed algorithm without the presence of EVs is presented in Fig. 4. The 'PF-1 Unit' is the load flow calculation block. It takes the load data and the grid data as the input. Wind data and solar data act as inputs for 'wind units' and 'PV panels', respectively. Then, it calculates the grid operating parameters, including voltages of different buses, and power flow through transformers and lines in the grid.

B. EV Effect

The details of EVs are explained in section II. As mentioned, the located EVs in each grid node are the aggregated model of the commuters and family cars for the node. Similar to solar panels, the penetration level of EVs for different nodes is with respect to the residential demand of the nodes. In this study, 20% EV penetration is considered. The proposed algorithm for grid analysis in presence of EVs can be seen in Fig. 5 and Fig. 6. The algorithm evaluates the grid without the effect of EVs, as shown in Fig. 5. Then, the results act as an input for 'EV Unit' block in this figure. The updated results with the effect of EVs are sent to "PF-3 Unit" for the grid analysis. Fig. 6 presents the "EV Unit" in details. As can be seen from Fig. 6, the algorithm takes the data from "PF-1 Unit", and checks the availability of all the EVs in different grid buses. If the EV is moving, it cannot be used for the grid support. Otherwise, the EVs will be sorted based on their state of charge (SoC). Then, the EV location (bus and feeder where the EV is connected) will be checked. Based on the maximum and minimum voltage of the feeder where the EV is connected (' V_{max} ' and ' V_{min} ' in Fig. 6), the algorithm decides how to use EV; either for positive balance (i.e. power from the grid to the EV), shown by $V2G(+)$, or for negative balance (i.e. power from EV to the grid), denoted by $V2G(-)$. The decision is made based on the voltage conditions (voltage set points), mentioned by 'Cond1' and 'Cond2' in Fig. 6. 'Cond1' and 'Cond2' represent the upper and lower limits for the voltage deviation of the feeder, which is obtained from Danish standard regulation [18]. In case where both conditions are satisfied (both 'Cond1' and 'Cond2'), the algorithm makes decision based on the distance between the EV bus and the buses which caused ' V_{max} ' and ' V_{min} ' in this interval. Based on the algorithm decision, the SoC of the EV and the "Load data" will be modified. Then, the "PF2" block analyses the grid to find the new status of the grid and to obtain the new values for ' V_{max} ' and ' V_{min} '. When all the EVs in the grid are analyzed, the results will be sent to "PF-3 Unit" in Fig. 5 for grid analysis in presence of the EVs.

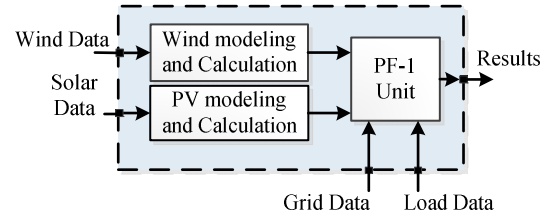


Fig. 4. Calculation process without EVs.

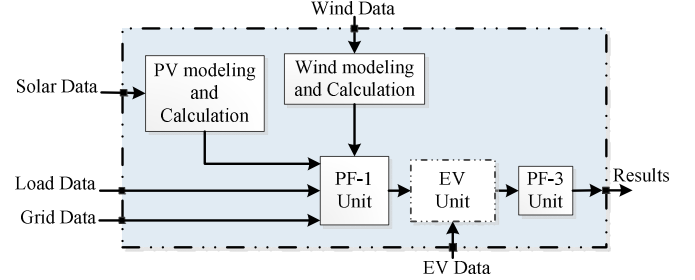


Fig. 5. Proposed algorithm in presence of EVs.

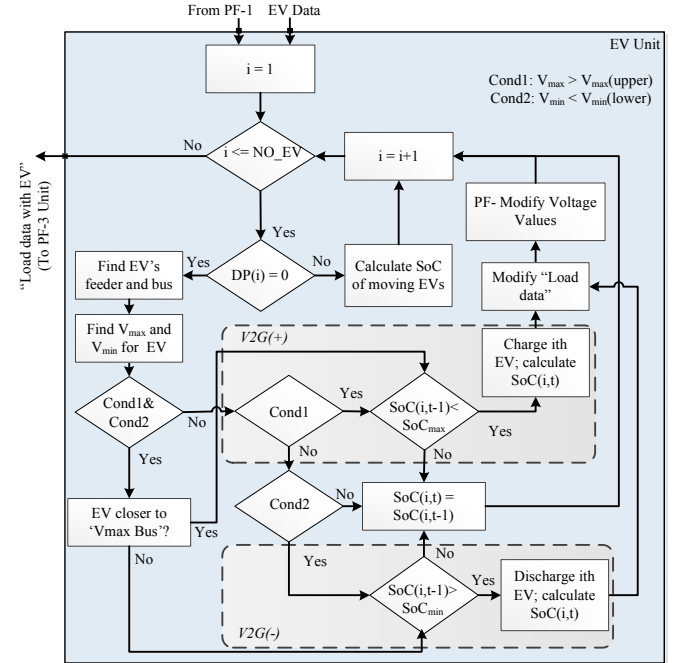


Fig. 6. EV Unit: the interaction between the grid and EVs.

V. CASE STUDIES AND SIMULATION RESULTS

To figure out the capability of EVs in dealing with high RES penetration, two summer scenarios and two winter scenarios have been simulated. The grid demand for each scenario is presented in Fig. 7. From the wind speed data, the wind production is much higher in a 'winter windy day', compared to other scenarios. Also, the load demand is much higher during the winter, compared to the summer days. As a comparison, Table III presents the output power of a 2-MW wind turbine for each of the scenarios. As mentioned in section III, the placement of solar panels in the grid is proportional to the residential demand of the grid buses, which is presented in Table I. In this study, it is assumed that the solar penetration is 20% in the grid. Table IV presents different placement of RESs

in the grid in each case study. From Table IV, the cases can be divided into 2 categories: a) cases where the wind turbine placement is near the load center (case 1 and case 2 in the table); b) cases where the wind turbines are located far from the load centers (case 3 and case 4 for feeder 1 in Fig. 1). In general, the wind turbines are preferred to be located at the buses far from the load centers [4]. The simulation results for different cases are presented below. As a major grid operating index, the voltage of different grid buses under different scenarios are presented and evaluated.

A. Grid Analysis without EVs

Table V presents the maximum voltage deviation of the grid. In this table, different possible RES scenarios are compared with the grid base case. To obtain the values of this table, the maximum and minimum voltage of each grid bus is calculated for each day. Then, the voltage deviation of each bus is obtained. Comparing the voltage deviations of different buses, the worst voltage deviation of the grid under a certain scenario is obtained. Analyzing different cases and scenarios, in cases where wind turbines are located at the remote buses, i.e. buses with a distance from the main transformer, the voltage deviation of the buses increases significantly. Case 3 and case 4 in Table IV represent such scenarios. Due to the structure of feeder 2, the high number of wind turbines doesn't cause serious voltage deviation, since the last bus on feeder 2 is a big load center. However, feeder1 has a different situation. Feeder 1 has many remote buses with low demand, such as bus 9, bus 10, and bus 11. Locating the wind turbines at these buses causes serious voltage deviations, as can be realized from case 3 and case 4 in Table V. In case 4, two wind turbines are located in the far end buses of feeder 1. In this case, although RESs cause no issues for transformers and the lines, the voltage deviations are quite significant. In case 3, only 3 wind turbines are located in the middle of the feeder, but the voltage deviation (especially bus 12 on feeder 1) exceeds 5%, which is a standard voltage deviation of the buses [18]. Such case needs to be handled by changing the tap changers of the transformers of the feeder, which is out of the scope of this study.

Considering the 20% solar penetration in this study, which is 2150 3-kW panels in the grid, and calculating the solar production for one year shows that panels provide around 2% of the grid annual demand in this study. However, most of the solar production is during the summer time, where the solar irradiation is high. Therefore, separating the summer and winter times during the year, and considering that the grid energy consumption in the summer is almost half of the grid consumption in the winter, the role of solar panels increases significantly for the summer scenarios. Separating the solar production of the grid for summer and winter scenarios suggests that the solar panels produce more than 95% of their annual energy production during the summer. Considering the 'solar' scenarios in Table V, in the summer scenarios, the solar panels lead to less voltage deviation on the MV grid. On the other hand, in cases where 'wind+ solar' exist in the grid, the solar panels have no significant effect on the voltages, as expected. Furthermore, in summer scenarios with 'low wind', solar panels helped to improve the voltage profile and reduce the voltage deviation. However, in 'windy day' of 'summer

scenario', the solar panels have negative effect on voltage deviations and increase the voltage deviations, compared to the cases where only 'wind' is in the grid.

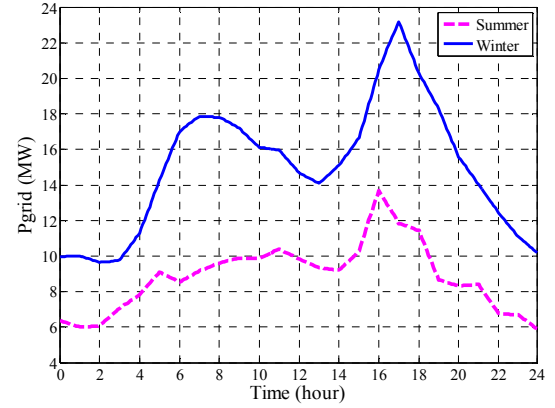


Fig. 7. Grid demand for summer and winter scenarios.

TABLE III. OUTPUT OF A 2-MW WIND TURBINE IN DIFFERENT SCENARIOS

		E_t (kWh)	P_{avg} (kW)	% of turbine capacity
Summer	Low wind	937.65	39.06	1.9
	Windy	24705.5	1029.4	51.47
Winter	Low wind	8776.2	365.67	18.3
	Windy	45811.2	1908.8	95.4

TABLE IV. DIFFERENT RES PLACEMENTS IN THE GRID

Bus No.	NO. Wind turbines				NO. Wind turbines + NO. PV panels			
	Case 1	Case 2	Case 3	Case 4	Case 1	Case 2	Case 3	Case 4
1	2	4	0	0	2+ 1000	4+ 1000	0+ 1000	0+ 1000
2	0	0	0	0	0+ 0	0+ 0	0+ 0	0+ 0
3	0	0	0	0	0+ 0	0+ 0	0+ 0	0+ 0
4	1	1	0	0	1+ 0	1+ 0	0+ 0	0+ 0
5	0	0	1	0	0+ 50	0+ 50	1+ 50	0+ 50
6	0	0	0	0	0+ 0	0+ 0	0+ 0	0+ 0
7	0	0	1	0	0+ 0	0+ 0	1+ 0	0+ 0
8	1	1	1	0	1+ 50	1+ 50	1+ 50	0+ 50
9	0	0	0	0	0+ 0	0+ 0	0+ 0	0+ 0
10	0	0	0	1	0+ 50	0+ 50	0+ 50	1+ 50
11	0	0	0	1	0+ 0	0+ 0	0+ 0	1+ 0
12	2	4	1	1	2+ 500	4+ 500	1+ 500	1+ 500
13	1	1	4	5	1+ 0	1+ 0	4+ 0	5+ 0
14	1	2	1	2	1+ 500	2+ 500	1+ 500	2+ 500

TABLE V. MAXIMUM VOLTAGE DEVIATION IN THE GRID FOR DIFFERENT WINTER AND SUMMER SCENARIOS

Scenario		Winter		Summer	
		Day 1: low wind	Day 2: windy day	Day 1: low wind	Day 2: windy day
Base		.0259	.0258	.0129	.0124
Scenario 1: Wind	Case 1	.0362	.0302	.0176	.0369
	Case 2	.0405	.0302	.0189	.0353
	Case 3	.046	.0367	.0223	.0556
	Case 4	.0402	.0332	.0196	.0448
Scenario 2: Wind + solar	Case 1	.0362	.0302	.0143	.0382
	Case 2	.0405	.0302	.0147	.0359
	Case 3	.046	.0367	.019	.0567
	Case 4	.0402	.0332	.0163	.0462
Scenario 3: Wind + solar + EV	Case 1	.0343	.0302	.0128	.0381
	Case 2	.0343	.0298	.0131	.0357
	Case 3	.0425	.0367	.0175	.0564
	Case 4	.0381	.033	.0147	.04608

In order to further clarify the impact of EVs on reducing voltage deviation in the grid, the maximum voltage deviation of case4 in Table V is presented and compared for different scenarios of case4 in Fig. 8. From Fig. 8, it can be realized that including EVs helps reducing voltage deviation in all the scenarios. However, for the ‘summer windy’ scenario, the impact of EV is insignificant. The reason is that both solar production and wind production have significant deviations in their power production in this scenario. As a result, considering the number of EVs in the grid for this study, the EV storage cannot effectively reduce voltage deviation in the grid.

B. Grid Analysis with EVs

To realize the effect of EVs on the grid, the voltage deviation of different scenarios in presence of EVs is presented in Table V. Comparing to the values for “wind+ solar” scenario in Table V, two points can be addressed. In the scenarios of “low wind” days, both in winter and in summer scenarios, the presence of EVs has helped reducing the voltage deviation in the grid. As the load demand increases during the evening time, the EVs start supporting the grid by injecting power into the grid (negative balance, V2G(-)). As a result, they help reducing voltage deviations in the grid. However, in the “windy” scenarios, the EVs hardly have a positive effect. The reason is that in these days, the power production of the wind turbines is very high, and it increases voltage of the grid buses. However, the EVs capacity for storing the extra energy is limited. Therefore, they have a very small effect on reducing the voltage deviations in these scenarios. It should be noted that the EV penetration is 20% in this study, as mentioned in section IV.B. To find out the EV interaction with the grid, the SoC of some of the grid EVs under some scenarios are presented below. Fig. 9 presents the SoC of grid EVs for ‘winter’ scenario, in ‘case 4’ with wind turbines and solar panels in the grid. From Fig. 9, in ‘low wind’ case, as the grid buses demand more energy and the wind power production is low, the EV role in supporting the grid is considerable (EV discharging for grid support). Especially, in the evening time, as the load demand increases, as presented in Fig. 9, the role of EVs becomes more significant. On the other hand, in ‘windy day’ case, due to high wind power production, the EVs are used by the grid to store energy, but their capacity is limited.

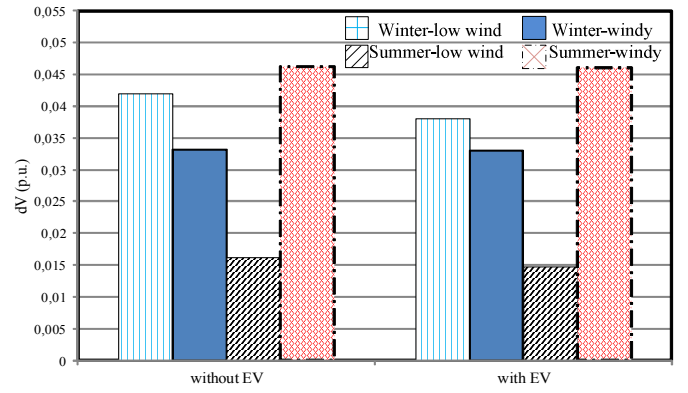


Fig. 8. Maximum voltage deviation in the grid for case4 in Table V: ‘without EV’ and ‘with EV’.

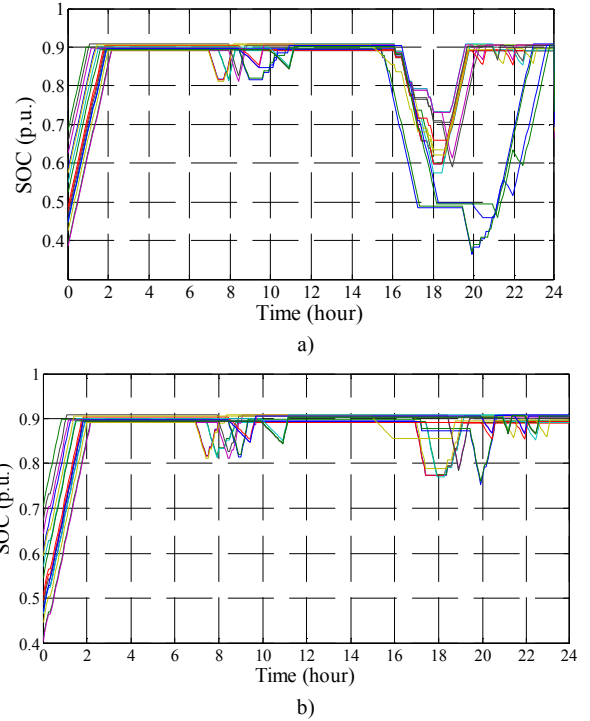


Fig. 9. SoC of EVs in case 4 (winter day): a) low wind; b) windy

An interesting fact about the presence of EVs in the grid is their role in increasing the penetration of wind turbines. From Table V, the voltage deviations on ‘low wind’ scenarios are higher than ‘windy’ scenarios. The presence of EVs reduces the maximum voltage deviation in ‘low wind’ scenarios, as mentioned above, and enables increasing wind penetration in the grid. For case 4 for ‘winter’ scenario with “wind+ solar”, the use of EVs allows installing at least 1 more 2-MW turbine at bus 9, without causing more than 5% voltage deviation.

C. RES Penetration

Considering the case scenarios in Table IV, it can be seen that for cases where the wind turbines are installed near the load centers, the overall RES penetration can increase significantly. As explained in section III, a 2-MW wind turbine can produce around 8.38% of the grid annual energy demand. Therefore, in cases where the wind turbines are installed near

the load centers, such as case 1 and case 2, the wind penetration can be increased to more than the grid annual energy demand (case 2 in this study). However, if the wind turbines are installed far from the load centers, the wind penetration level will be limited by voltage deviation. For the CIGRE grid in Fig. 1, case 3 and case 4 represent the cases where the wind turbines are installed far from the load centers on feeder 1. Although the overall wind penetration is still high in these cases (up to 85% of the grid annual energy demand in case 4), feeder 1 has serious limits in these scenarios. Due to high voltage deviations, the maximum wind penetration for this feeder is around 17% of its annual energy demand. However, as mentioned above, the use EVs enables installing at least 1 more 2-MW wind turbine, which leads to 8.35% higher wind penetration. Therefore, the overall wind penetration on feeder 1 can increase from 17% to 25%.

VI. CONCLUSION

The high penetration of RESs in a standard CIGRE MV grid has been analyzed and investigated in this paper. Different scenarios, with different placements of wind turbines in the grid, are analyzed. Also, the presence of residential solar PV panels in the grid was investigated to realize the grid limits in dealing with high RES penetration. Results show that, for the winter loading in the grid, the main players are the wind turbines, as the solar power production is very low. Locating the wind turbines on remote buses, i.e. buses that are far from the main transformer and load centers, results in huge voltage deviations (such as 'case 3' and 'case 4' in Table IV). Analyzing the cases where solar panels are placed in the grid show that, in almost all scenarios, the solar panels have had a positive effect on the grid and reduced the voltage deviation among the grid buses, compared to similar scenarios without the solar panels. However, among all the cases, 'case 3' of the 'windy summer day' with both wind turbines and solar panels in the grid shows maximum voltage deviation. Two parameters cause such deviation. The first parameter is the location of the wind turbines, which are located in the remote buses. The second reason is the significant solar power production in the summer scenario.

EVs, as one of the grid flexible loads, are used in this study for grid support applications. Considering the number of EVs in this scenario, i.e. 1000 EVs in the grid, EVs have a high potential of participating in the upper network regulation, either for negative balance (where the grid requires power), such as a 'low wind', or for positive balance (where there is extra power in the grid).

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